MINISTRY OF FISHERIES
Te Tautiaki i nga tini a Tangaroa

ISSN 1175-1584

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R. I. C. C. Francis
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New Zealand Fisheries Assessment Report 2004/3
January 2004

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R. I. C. C. Francis
R. L. O'Driscoll

NIWA
Private Bag 14901
Wellington

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Published by Ministry of Fisheries
Wellington
2004

ISSN 1175-1584

Citation:
Francis, R.I.C.C.; O'Driscoll, R.L. (2004).
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combining acoustic and trawl data.
New Zealand Fisheries Assessment Report 2004/3. 28 p.

This series continues the informal
New Zealand Fisheries Assessment Research Document series
which ceased at the end of 1999.

EXECUTIVE SUMMARY

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Acoustic surveys of spawning hoki on the west coast South Island (WCSI) require a large trawling component to determine the proportion of hoki in mixed species marks in the area north of Hokitika Canyon. If trawling is carried out like that in a random trawl survey, then the trawls provide another fisheries independent estimate of hoki abundance

Simulation studies based on results from the previous WCSI survey in 2000 suggested that there would be a gain in information by switching from the current method of producing one acoustic abundance index for the whole WCSI to a new method where three relative biomass estimates are produced – a northern acoustic index, a southern acoustic index, and a northern trawl index. Estimates based on the best available information suggested that the gain from making this change would be equivalent to reducing a simple survey c.v. from 0.31 to 0.21.

This report proposes a survey design for a WCSI survey in 2004 based on this new method. The survey area was the same as in 2000. The northern area consists of two main strata (Strata 1&2 and 4), sub-stratified by depth, and the southern area has four strata (Strata 5A, 5B, 6, and 7). Because separate abundance indices are produced for northern and southern areas, the number and timing of acoustic snapshots in the two areas could differ. It is anticipated that the northern acoustic estimate would have fewer snapshots than previous surveys because of the time needed to carry out random trawls. Simulations of survey uncertainty using the best available information indicated that acoustic surveys of WCSI should have a mid-date of about 5 August in both areas. Increasing the number of snapshots reduced the c.v. in the northern area, but was much less important than survey timing in the south. Longer surveys with more snapshots were also more robust to assumptions about the timing of spawning than shorter ones. In both areas, simulations suggested there was little advantage in having a survey with more than four snapshots.

Optimisation based on trawl catch rates from 2000 suggest that 51 random bottom trawls would be required in the northern area to achieve target c.v.s of 20% for hoki, hake, and ling, and 25% for silver warehou. All bottom trawls should be carried out during the day when a greater proportion of fish are near the bottom and catch rates are higher.

The minimum recommended requirement for a combined survey in 2004 is two acoustic snapshots in the northern area, a northern trawl estimate, and three acoustic snapshots in the southern area. This would require about 23 vessel days on the WCSI grounds. To allow comparison with 2000, all random trawls should be carried out from *Tangaroa* using the eight-seam hoki bottom trawl. There is no specific vessel requirement for the rest of the acoustic survey.

1. INTRODUCTION

Hoki is New Zealand's largest fishery with a current TACC of 200 000 t. The main fishery occurs on the west coast South Island (WCSI), where hoki spawn during June to September. The WCSI fishery accounted for 47% of the hoki catch in 2001–02 (Annala et al. 2003). Acoustic surveys have provided relative abundance indices for spawning hoki on the WCSI since 1988, with annual surveys from 1988–93, and then in 1997, and 2000 (review by O'Driscoll 2002).

There was much uncertainty associated with abundance indices from the two most recent acoustic surveys of the WCSI in 1997 (Cordue & Ballara 1998) and 2000 (Cordue 2002) because of problems with species mix in the northern strata. Acoustic methods work best where fish occur in readily identifiable single-species aggregations. Hoki do form such aggregations during spawning on the WCSI, particularly in Hokitika Canyon. However, away from the main spawning areas hoki typically occur in a bottom-oriented, low-density layer which also contains other species. Because these mixed species layers occur over relatively wide areas, they can account for a significant portion of the total hoki biomass (O'Driscoll et al. 2004). To estimate hoki biomass in mixed species layers, it is necessary to partition the acoustic backscatter based on the composition of trawl catches (Cordue 2002, O'Driscoll 2002). This means that any WCSI survey requires an extensive trawling component (Rose 1998).

This report describes work carried out as part of Objective 4 of MFish project HOK2002/03: *To design an acoustic survey of the west coast South Island (WCSI) spawning area to be carried out in 2004*. The report is in two main parts. The aim of Sections 2–7 is to determine whether more use can be made of trawl data in acoustic surveys of hoki on the WCSI. Section 8 of the report proposes a design for a 2004 survey based on the results of the first study, and also incorporating recommendations from a reanalysis of trawl and acoustic data from the previous WCSI survey in 2000 by O'Driscoll et al. (2004).

2. COMBINING ACOUSTIC AND TRAWL DATA FOR WCSI HOKI

Current practice is to use some information from trawls that are done during the acoustic survey to solve what is called the species mix problem — i.e., to determine what fraction of the echo signal is from hoki. Another way the trawl data could be used is to calculate an estimate of relative hoki abundance like that from a random trawl survey (e.g., O'Driscoll et al. 2004). The question is whether this abundance index, which would cover only part of the survey area, would be useful as a stock assessment input, in addition to the acoustic index.

There is a good reason to say that the trawl index would cover only part of the survey area. We may think of the WCSI acoustic survey area as divided into north and south areas. In the north there is a clear species mix problem so there is a need to carry out many trawls to estimate the species mix. Also, this is a good area in which to get a trawl-survey estimate of abundance because there tend not to be large concentrations of hoki. In the south, hoki make up a larger proportion of the biomass and often occur in dense concentrations. This means there is not as much need for trawls to estimate species mix and trawl-survey estimates of abundance would be unreliable. Thus, it is sensible that any trawl abundance estimate should apply only to the northern area. Our aim is to compare the conventional survey (which we will call the "old" design), in which we just have an acoustic estimate for the whole survey area, with a "new" design in which we also have a trawl estimate for the northern area.

There is a trade-off involved between the new and old designs. For the new design, more time must be spent on trawling because we must trawl at randomly selected locations (as in a stratified random trawl survey), rather than just fishing wherever is convenient. This means that less time will be spent on acoustic transects, so the acoustics biomass estimate will be less precise (assuming that the same total time is available for old and new designs). Thus, our job is to determine whether, if we were to switch to the new design, the additional information in the trawl biomass estimate would compensate for the loss of acoustic precision.

It will be assumed throughout that the acoustic biomass estimates are relative only. In some settings acoustic surveys can produce estimates of absolute abundance, but that is not possible for hoki in WCSI because of the problems produced by turnover (Coombs & Cordue 1995).

The ideas presented here, and the methods of exploring them, are quite similar to those of Francis (2003). He also considered combined acoustic and trawl surveys, but in his surveys there was no overlap between the coverage of the acoustic and trawl components, and neither component covered the whole survey area.

We first develop a statistical model showing how information from the new design could be used in a stock assessment. Within this model there will be seen to be more than one method of analysing the data from each of these designs. Then we carry out a simulation experiment to compare the old and new designs, as well as the various methods of analysis.

3. STATISTICAL DESIGN

Our statistical design is in two parts: an error model for our observations, and a population dynamics model to which these observations are to be fitted.

For the error model, denote by B_i the true hoki biomass in year i, and let π_{Ni} be the proportion of this biomass that is in the northern area, for $i = 1,...,n$. Let our observations (i.e., our survey biomass estimates) be O_{ASi}, O_{ANi}, and O_{TNi}, where A and T refer to acoustic and trawl, and N and S to north and south (in an old survey we would have just the first two indices, but in the new survey we would have all three). We will assume that the biomass estimates are lognormally distributed with means $q_A(1-\pi_{Ni})B_i$, $q_A\pi_{Ni}B_i$, and $q_T\pi_{Ni}B_i$, respectively, and known coefficients of variation (c.v.s), c_{ASi}, c_{ANi}, and c_{TNi}. Because some of the uncertainty associated with the two acoustic estimates is common to them both (e.g., uncertainty in the target strength of hoki) we will also assume a known correlation between them, denoting by ρ_A the correlation between $\log(O_{ASi})$ and $\log(O_{ANi})$. We also allow a correlation ρ_T between $\log(O_{TNi})$ and $\log(O_{ANi})$ because high trawl catches of hoki, which produce high values of O_{TNi}, also tend to indicate that a high proportion of the echo signal from mixed schools is caused by hoki, and thus cause high values of O_{ANi}.

Our population dynamics model is very simple and quite artificial: we assume that the population is growing at a rate of p% per year, so $B_i = B_{\text{init}}(1+p/100)^i$. Our only stock assessment task is to estimate the rate of growth, p (which could be positive or negative), over the period of the surveys. Whichever survey design provides the better (more accurate) estimate of p will be deemed the better design. We chose such a simple model because it makes the analysis straightforward. In the much more complex setting of a normal population dynamics model the information content of our surveys will depend on many factors, including the catch history and what other observations are available. However, our focus in this study is on which type of survey design provides more information; the absolute quantity of information contained in the survey data is of less interest in this setting.

There are three methods of analysing an old survey, and these differ in how they treat the π_{Ni}. The conventional approach is the simplest, and this ignores the π_{Ni}. The two estimates from the survey are added to make a single index, O_{Ai} (= $O_{ANi} + O_{ASi}$), which has expected value q_AB_i, so the π_{Ni} disappear from the observation error model. A second method ignores year-to-year variation and so sets $\pi_{Ni} = \pi_N$ for all i. This has the merit of reducing the number of parameters that have to be estimated. The third approach involves estimating a value of π_{Ni} for each year. We will refer to these three methods as old.none, old.fix, and old.est, respectively.

For the new type of survey only the last two of these methods (which we will label new.fix and new.est) will work. For a new survey there's no incentive to use O_{Ai} in place of O_{ANi} and O_{ASi} (as we do for old.none) because (a) it would deprive the assessment model of information it needs to relate the trawl indices, O_{TNi}, to the acoustic data, and (b) it wouldn't cause the π_{Ni} to disappear (they'd still be present in the expected value of the O_{TNi}).

Thus, we have a total of five methods to investigate, and each implies a different set of parameters to estimate (Table 1). However, we shall be concerned with only one parameter, p, which is estimated for all methods. Estimation will be by maximum likelihood (see Appendix 1 for equations). Note that it is not possible, with this simple assessment model, to estimate either B_{init} or the catchabilities, q_A and q_T, though we can estimate their product. In a proper stock assessment setting a catch history would be available, and it is this, in conjunction with relative biomass indices, which would allow the estimation of absolute biomass.

Table 1: Details of the five methods to be evaluated. Each method is defined by a survey design (old or new), and the assumptions that are made about the π_{Ni}. The subscript i on parameters indicates there is one parameter for each year in which there is a survey.

Method	Survey design	Observations	Assumptions about π_{Ni}	Parameters to estimate	Known parameters
old.none	old	O_{Ai}	ignore	p, $q_A B_{init}$	c_{Ai}
old.fix	old	O_{ANi}, O_{ASi}	assume $\pi_{Ni} = \pi_N$ for all i	p, $q_A B_{init}$, π_N	c_{ANi}, c_{ASi}, ρ_A, ρ_T
old.est	old	O_{ANi}, O_{ASi}	none	p, $q_A B_{init}$, π_{Ni}	c_{ANi}, c_{ASi}, ρ_A, ρ_T
new.fix	new	O_{ANi}, O_{ASi}, O_{TNi}	assume $\pi_{Ni} = \pi_N$ for all i	p, $q_A B_{init}$, $q_T B_{init}$, π_N	c_{ANi}, c_{ASi}, c_{TNi}, ρ_A, ρ_T
new.est	new	O_{ANi}, O_{ASi}, O_{TNi}	none	p, $q_A B_{init}$, $q_T B_{init}$, π_{Ni}	c_{ANi}, c_{ASi}, c_{TNi}, ρ_A, ρ_T

4. UNCERTAINTY IN WCSI ACOUSTIC SURVEYS

This section describes two sets of information from past acoustic surveys that were be used in the simulation experiment to define the level of uncertainty in simulated data.

Our first set of information concerns π_N. Estimates from acoustic surveys tend to be lower and vary less from year to year than those from catches (Table 2).

Table 2: Estimates of the proportion of WCSI hoki biomass in the northern area (π_N) from acoustics surveys and spawning season catches.

Year	Acoustics	Catch
1988	0.34	–
1989	0.10	–
1990	0.14	0.29
1991	0.11	0.36
1992	0.20	0.54
1993	0.18	0.76
1994	–	0.73
1995	–	0.62
1996	–	0.49
1997	0.36	0.60
1998	–	0.58
1999	–	0.40
2000	0.25	0.59
2001	–	0.38
2002	–	0.41
Mean	0.21	0.52
Standard deviation	0.10	0.15

Our other set of information is a matrix which describes the uncertainty in acoustic and trawl estimates. The matrix was generated using a simulation procedure that combines uncertainty from each of five main sources:

- assumptions, about timing and duration of spawning and residence time, for the plateau model of Cordue (1989)
- sampling precision
- mark identification
- fish weight and target strength
- acoustic calibration

The simulation method was very similar to that used to estimate the weightings (c.v.s) for acoustic surveys used in stock assessment, and described in detail by O'Driscoll (2002), except that four acoustic uncertainty distributions were estimated instead of one. The four distributions were for S5, N2, N3, and N5, where S and N refer to the south and north parts of the survey area and the digit is the number of snapshots in a survey.

Values of parameters and their probability distributions were based on data from the 2000 survey because this is the only year with a large number of random trawls. In each simulation a biomass model was constructed by randomly selecting values for arrival date and residence time from the distributions in Table 3. This model was then "sampled" at dates equivalent to the mid dates of each snapshot (Table 4). A sampling uncertainty was applied to each column based on c.v.s estimated from the snapshots in 2000 (Table 4). In the northern area, the uncertainty in the trawl estimate of species mix was determined from a bootstrapped sample of 50 trawls from those carried out in 2000. Catch rates from the same 50 trawls were used to estimate a corresponding trawl biomass (T) for each simulation. There is a correlation between the trawl and northern acoustic estimates because the proportion of hoki in a trawl used to estimate species mix and the catch rates of hoki are strongly correlated (O'Driscoll et al. 2004). Uncertainty due to mark identification (which was much greater in the north than in the south) was then applied. The same random values for calibration and TS were applied to both northern and southern areas. Acoustic estimates from all snapshots were averaged to produce an abundance index for each "area". This whole process was repeated 5000 times to generate a matrix of five columns (S5, N2, N3, N5, and T) and 5000 rows.

Table 3: Values of parameters and their distributions used to construct the acoustic uncertainty matrix.

		Values*	
Parameter	Distribution	North	South
Mean arrival date, $\bar{d}$	Uniform	197–212	197–212
Mean residence time, $\bar{r}$	Uniform	27–47	27–47
Individual arrival date	Normal	$\bar{d}$ (5)	$\bar{d}$ (5)
Individual residence time	Normal	$\bar{r}$ (10)	$\bar{r}$ (10)
Sampling (see Table 4)	Normal	1.0 (snapshot c.v)	1.0 (snapshot c.v)
Trawl estimate of species mix	Bootstrap	n = 50 trawls	–
Mark identification	*Lognormal*	0 (0.32)	0 (0.08)
Calibration	Uniform	0.95–1.05	0.95–1.05
Target strength	Uniform	0.88–1.12	0.88–1.12

*For uniform distribution values are ranges; for normal distributions values are means with s.d. in parentheses; for lognormal distributions values are the mean and s.d. of $\log_{10}$(variable). Plateau model variables (mean and individual arrival dates, mean and individual residence times) are in days. All other variables are relative (scaled to 1).

Table 4: Snapshot dates and sampling c.v.s used to construct the acoustic uncertainty matrix.

S5		N2		N3		N5	
Date	c.v.	Date	c.v.	Date	c.v.	Date	c.v.
28 Jul	0.12	3 Aug	0.08	28 Jul	0.13	28 Jul	0.13
3 Aug	0.12	19 Aug	0.20	10 Aug	0.12	3 Aug	0.08
10 Aug	0.10			26 Aug	0.25	10 Aug	0.12
19 Aug	0.09					19 Aug	0.20
26 Aug	0.08					26 Aug	0.25

To simulate a new survey with, say, five southern and two northern snapshots, we simply pick a number j at random between 1 and 5000 and set $O_{AS} = \mathrm{S5}(j)(1-\pi_N)q_AB$, $O_{AN} = \mathrm{N2}(j)\pi_Nq_AB$, and $O_{TN} = \mathrm{T}(j)\pi_Nq_TBr$, where B is the true biomass for the whole area and r is a random number from a lognormal distribution with mean 1 and c.v. 0.2 which allows for between-year variability in catchability (following Francis et al. 2003). It is important to select the same row of the matrix for the each biomass index because there are correlations between the columns (Table 5). The c.v. of the total acoustic biomass estimate will depend on the number of northern transects and the proportion of biomass that is in the northern area (Figure 1). Plots of cumulative distribution functions for each column (not shown) showed that they are reasonably well approximated by a lognormal distribution.

Table 5: Some statistics of the uncertainty matrix which are used in the simulation experiment.

		Value				
Statistic	Symbol	S5	N2	N3	N5	T
Coefficient of variation	c_{AS} or c_{AN}	0.27	0.74	0.63	0.52	0.29[1]
Correlation with S5 (in log space)	ρ_A		0.42	0.46	0.55	
Correlation with S5 (in natural space)	ρ_{An}		0.34	0.40	0.49	
Correlation with T (in log space)	ρ_T		0.15	0.17	0.21	

[1] Includes and allowance for annual variation in trawl catchability

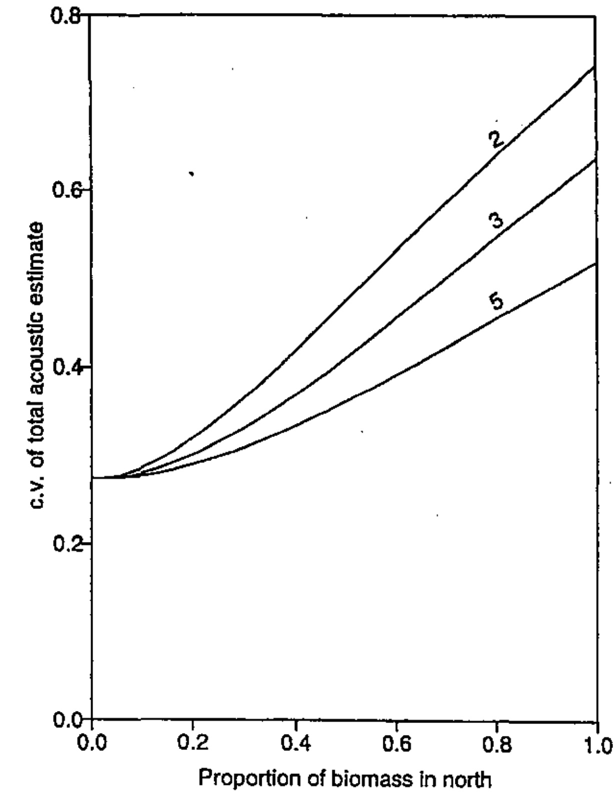

Figure 1: The relationship between the c.v. of the total acoustic estimate, c_A, and the proportion of biomass in the northern area, π_N, for simulated surveys with 2, 3, or 5 northern snapshots.

5. SIMULATION EXPERIMENT

The simulation experiment included many scenarios, each of which was defined by specifying values for all the parameters of Table 6. For each scenario, 500 data sets were simulated, and the maximum-likelihood methods of Appendix 1 were used to calculate, for each of our five methods, an estimated population growth rate, p, for each data set. Two performance measures were calculated for each method in each scenario: root-mean-square error, rmse = $\left[(1/500)\sum_k(\hat{p}_k - p_{\text{true}})^2\right]^{0.5}$, and bias = $\bar{p} - p_{\text{true}}$, where $\hat{p}_k$ is the growth-rate estimate for the kth data set, $\bar{p}$ is the mean of the $\hat{p}_k$, and p_{true} is the true growth rate. An approximate 95% confidence interval was calculated for each performance measure (following Francis 2003).

Our primary performance measure is rmse. We consider that our estimates of population growth are good if rmse is small, and poor if it is large, regardless of the level of bias. The reason for calculating bias is to indicate whether the rmse is mostly caused by bias or imprecision (i.e, variance) in the estimator. Since $\text{rmse}^2 = \text{bias}^2 + \text{variance}$, we can measure the percentage contribution of bias to rmse as $100\ \text{bias}^2/\text{rmse}^2$. If this contribution is less than 10% we will say that the bias is negligible.

Table 6: Parameters used to define scenarios in the simulation experiment, with their base values and the alternative values used in the first set of scenarios. Where different parameter values were used in old and new surveys these are identified with the superscripts 'o' or 'n'.

Symbol	Description	Base	Alternative
B_{init}	initial biomass	1	–
q_A	acoustic catchability	1	–
q_T	trawl catchability	1	–
n	number of years with surveys	5	3,10
p	annual percentage growth in population biomass	0	-5,5
m_N	number of snapshots in north in new surveys	2^n	3^n,5^n
c_{AS}	c.v. of acoustic biomass estimate in south	0.27	
c_{AN}	c.v. of acoustic biomass estimate in north	0.52^o,0.74^n	0.63^n,0.52^n
c_{TN}	c.v. of trawl biomass estimate	0.29^n	–
ρ_A	acoustic correlation (log space)	0.55^o,0.42^n	0.16^n,0.40^n,0^n
ρ_{An}	acoustic correlation (natural space)	0.49^o	–
ρ_T	trawl correlation (log space)	0.21^o,0.15^n	0.17^n,0.21^n,0^n
μ_π	mean proportion of biomass in north	0.2	0.5
σ_π	s.d. of proportion of biomass in north	0.1	0.15,0
τ	trend in π_N	0	-0.34,0.34

The following steps were followed in simulating data from a single survey in year i:

1. Calculate the true biomass in year i, $B_i = B_{\text{init}}(1+p/100)^i$
2. Calculate the expected π_N in year i, $\mu_{\pi i} = \mu_\pi \exp\left[\tau(i - \bar{i})\right]$
3. Simulate π_{Ni} by generating a number from a beta distribution with mean $\mu_{\pi i}$ and s.d. σ_π (the beta distribution is convenient because it is confined to the interval [0,1]).
4. Generate O_{ANi} and O_{ASi} (and O_{TNi} if required) from the uncertainty matrix, as described in the previous section
5. If the method is old.none estimate c_{Ai} as

$$(1/O_{Ai})\left[(O_{ANi}c_{AN})^2 + (O_{ASi}c_{AS})^2 + 2\rho_{An}O_{ANi}c_{AN}O_{ASi}c_{AS}\right]^{0.5}$$

We now describe how base and alternative values were assigned for each parameter of Table 6. The first three parameters (B_{init}, q_A, and q_T) are simply scale factors whose values are immaterial, so all were arbitrarily set to 1. For n, 3 is the smallest value for which the surveys can have much use, 10 is a value which allows us to evaluate the medium-term utility of the surveys, and 5 is a convenient value in between. An analysis of biomass trajectories from the most recent hoki stock assessment showed that the median absolute percentage change in biomass from year to year was about 5% (authors' unpublished data), so a central value of 0 was set for p, with alternative values of +5 and –5. The parameter m_N is included because it is expected that a new survey would have fewer northern acoustic snapshots because of the need to spend more time trawling. All old surveys had five snapshots (as in the 2000 survey) but new surveys had only two snapshots for the base scenario (alternatives of three and five were also considered). The c.v.s and correlations (c_{AN}, c_{AS}, c_{TN}, ρ_A, ρ_T, and ρ_{An}) depend on m_N and values were taken from Table 5. Base and alternative values of μ_π and σ_π are rounded from the bottom rows of Table 2. The alternative values of τ were chosen so that the expected value of π_N in a 5-year survey series varied from half to double its value in the middle year.

We must make a distinction between the role of these parameters in simulating the data and in analysing them in a stock assessment. Some parameters (n, m_N, c_{AS}, c_{AN}, c_{TN}, ρ_{An}) were assumed known in the stock assessment, and the values used were the same as in simulating the data. The parameters ρ_A and ρ_T also fell into this category except that for one scenario (ρ=0) the data were simulated using the base values but analysed assuming $\rho_A = \rho_T = 0$. The remaining parameters (B_{init}, q_A, q_T, p, μ_π, σ_π, τ) were treated as unknown in the assessment.

The same random number seed was used for all scenarios in order to increase comparability between scenarios from the same set.

6. SIMULATION RESULTS

The first set of scenarios consisted of a base scenario (which used the base values for all parameters) and a series of alternative scenarios, in each of which one or two parameters took alternative values. For example, in the scenario labelled n=3 all parameters were at their base values except for n which was set to 3.

The rmse values from this set (Figure 2) allow the following conclusions (bearing in mind that a lower rmse value means a more accurate estimate of p). For old surveys, the three estimation methods produce very similar results except that old.fix was markedly worse than the others in two scenarios (μ_π=0.5,σ_π=0.15 and τ=-0.34). old.none was slightly better than old.est in all but one scenario, where it was slightly worse (but there was always substantial overlap in the rmse confidence intervals for these two methods). For new surveys, new.est was almost always clearly better than new.fix, the only exception being when there was no variation in π_N (scenario σ_π=0). Comparing new and old surveys, new.est was always better than all old survey methods.

When there was no trend in π_N, bias values were typically small and positive (Figure 3), with the percentage contribution of bias to rmse being negligible (in the sense defined in Section 5). This contribution became substantial with new.fix and old.fix when $\tau \neq 0$ (Table 7).

Table 7: Percentage contribution of bias to rmse for scenarios in which $\tau \neq 0$.

	Method				
Scenario	old.none	old.fix	old.est	new.fix	new.est
τ=-0.34	0.0	43.7	0.1	63.9	3.1
τ=0.34	4.9	32.0	6.9	55.4	13.1

These results show that in choosing the best analysis method for an old or new survey design the parameters affecting π_N (i.e., μ_π, σ_π, and τ) are important. In our second set of scenarios only these parameters were allowed to vary, with all other parameters fixed at their base values. rmse estimates from these scenarios confirm that old.none is to be preferred to old.fix because its rmse was sometimes substantially lower and never substantially higher (Figure 4). Also, new.est is preferable to new.fix for similar reasons.

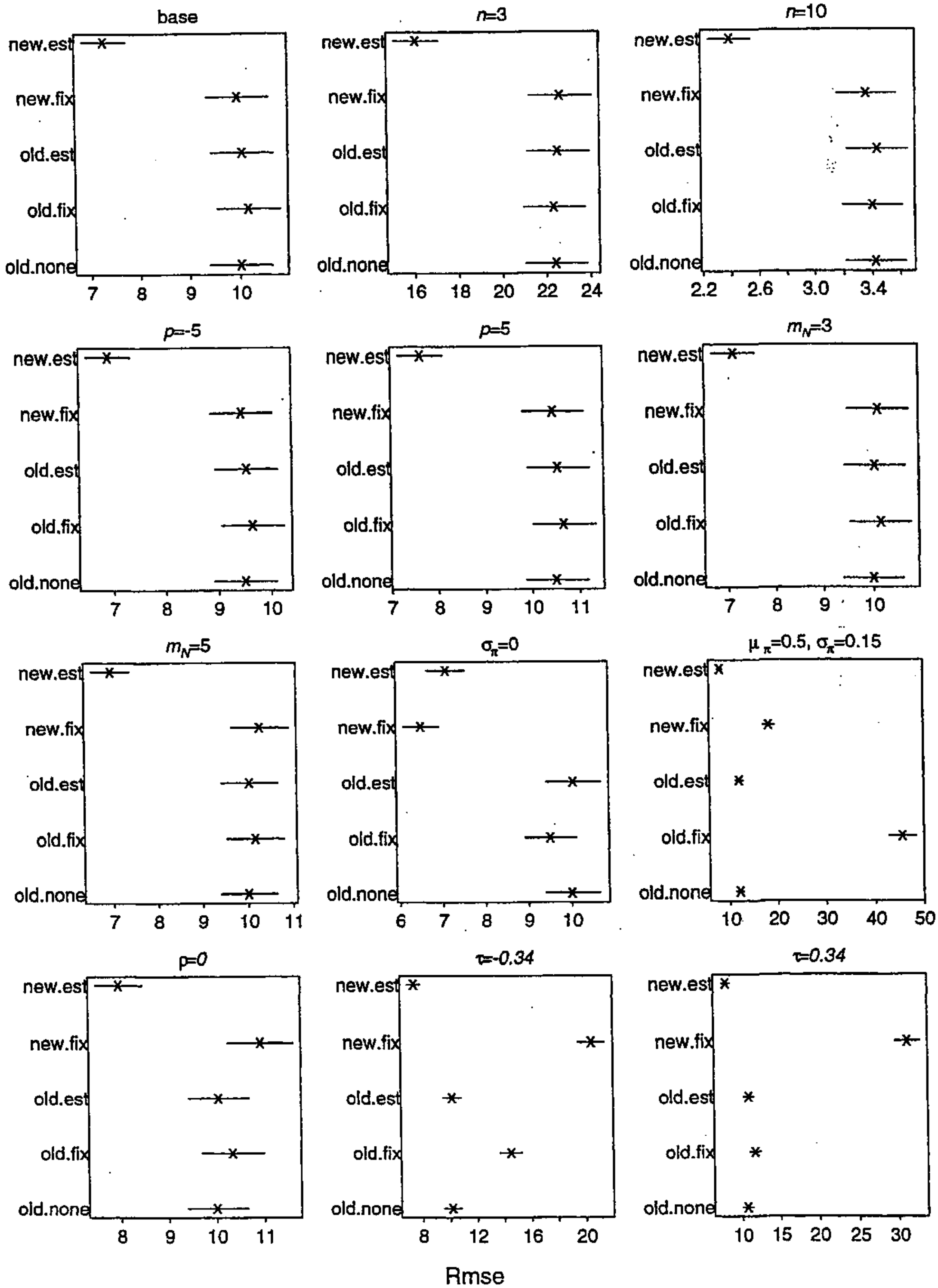

Figure 2: Rmse values from the first set of scenarios. Each panel corresponds to a scenario and shows estimates of rmse ('x') with 95% confidence intervals (horizontal bars) for each of the five survey methods (old.none, old.fix, old.est, new.fix, new.est).

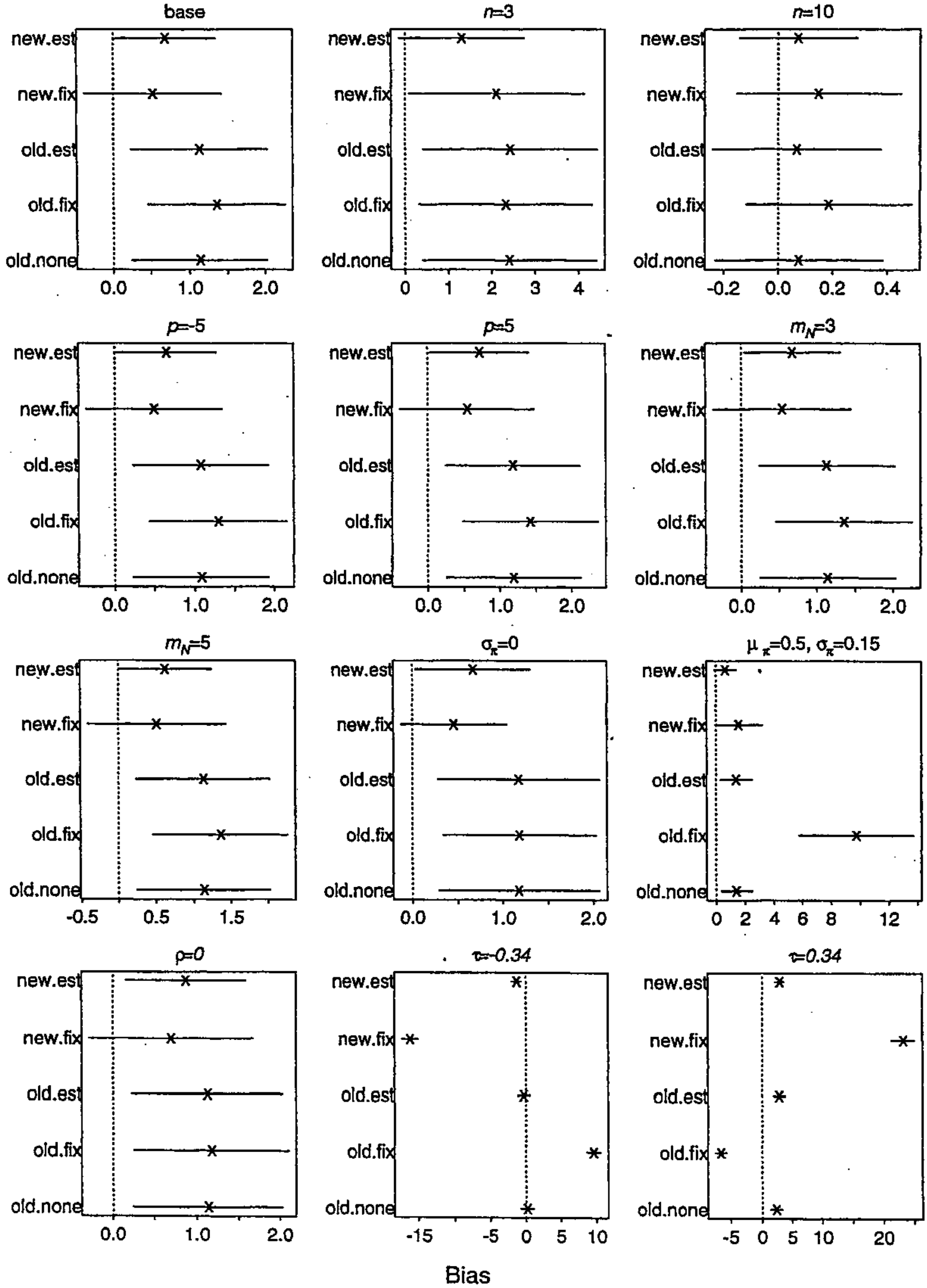

Figure 3: Bias values from the first set of scenarios. Each panel corresponds to a scenario and shows estimates of bias ('x') with 95% confidence intervals (horizontal bars) for each of the five survey methods (old.none, old.fix, old.est, new.fix, new.est).

In the remaining results we restrict attention to methods old.none and new.est. The parameter which had the greatest effect on rmse in our initial scenarios was n. A third set of scenarios illustrates how rmse decreases as n increases, and shows that five years of surveys with method new.est gives approximately the same precision as six years with the traditional method, old.none (Figure 5).

Another way of comparing these methods is on the basis of "equivalent" c.v.s. We can ask what c.v. would a simple survey (producing a single biomass estimate) need to have to produce the same precision (i.e., the same rmse) as these methods. For the base scenario the equivalent c.v.s were found to be 0.31 for method old.none, and 0.21 for method new.est. (To obtain these results we needed to establish the relationship between rmse and the c.v. of a simple survey. Simple survey data were simulated using a lognormal distribution and a range of c.v.s, and p was estimated using the equation for method in Appendix 1.)

Figure 6 shows that the effects of those parameters not discussed so far are relatively slight. rmse increases slightly with increasing p (for reasons that are unclear). The decrease in rmse as m_N increases is as expected. Finally, ignoring the correlations (i.e., setting $\rho_A = \rho_T = 0$ in the assessment) decreases precision (increases rmse) slightly.

7. DISCUSSION OF SIMULATION RESULTS

The above results indicate that it would be advantageous to change from the current method for WCSI acoustic surveys (here called old.none) to a new method (new.est). Estimates based on the best available information (the base scenario) suggest that the gain in information from making this change would be such that five years of surveys of the new design would be approximately equivalent to six years of surveys with the old design. Another way of expressing the comparison is to say that changing from old.none to new.est is the equivalent to reducing a simple survey c.v. from 0.31 to 0.21.

The proposed change in method, which is cost neutral, has three parts. First, trawling in the northern area should be at random (following a stratified random survey design) rather than being targeted at selected acoustic marks. This will make the trawling component of the survey more time-consuming, which means that fewer acoustic snapshots will be possible. Second, the analysis of the survey should change to produce three biomass estimates (acoustic for the south, and acoustic and trawl for the north), rather than a single acoustic estimate. Third, the way these three estimates should be used in a stock assessment should be like that described here for method new.est.

We emphasise that the above simulations were not intended to address the question of whether there should be a WCSI acoustic survey in 2004. That question is outside the scope of the objectives of this work (see Section 1). We address only the question of what form the survey should take if there is to be one.

In the interests of simplicity we recommend ignoring the two correlation terms, ρ_A and ρ_T, in the likelihood for new.est. In the simulations, where these were assumed to be known exactly, excluding them from the likelihood produced a slight loss of precision (compare the estimated rmse for the base and ρ=0 scenarios in Figure 6). In reality, they will not be known exactly, so using estimated values is likely to produce little if any gain in precision.

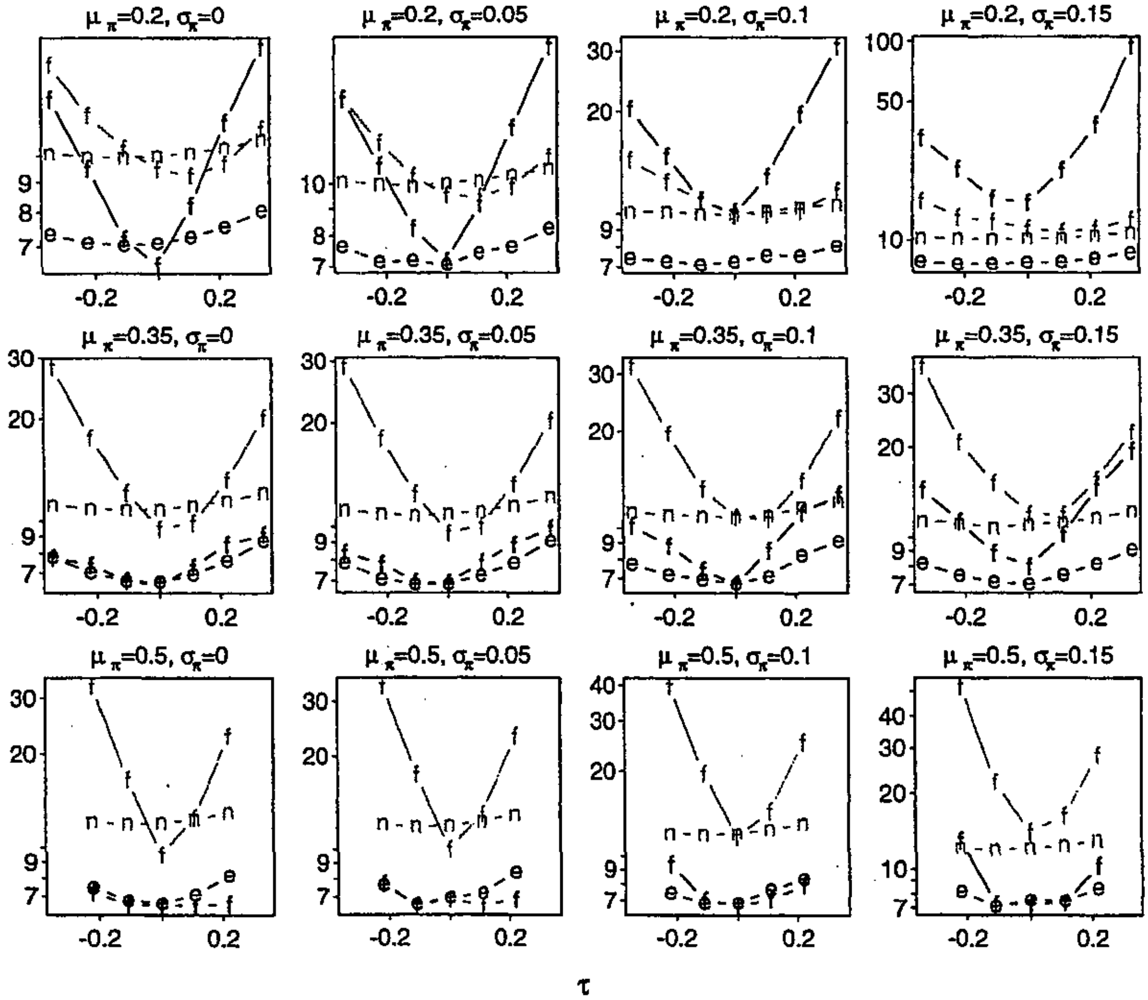

Figure 4: rmse estimates for four methods (old.fix, old.none, new.fix, new.est) from a second set of scenarios. Each panel shows the results from scenarios in which τ varied for the fixed values of μ_π and σ_π shown above the panel, and the method is identified by the plotting symbol ('f' = fix, 'n' = none, 'e' = est) and colour (black = new, grey = old). For these scenarios all other parameters were fixed at their base values.

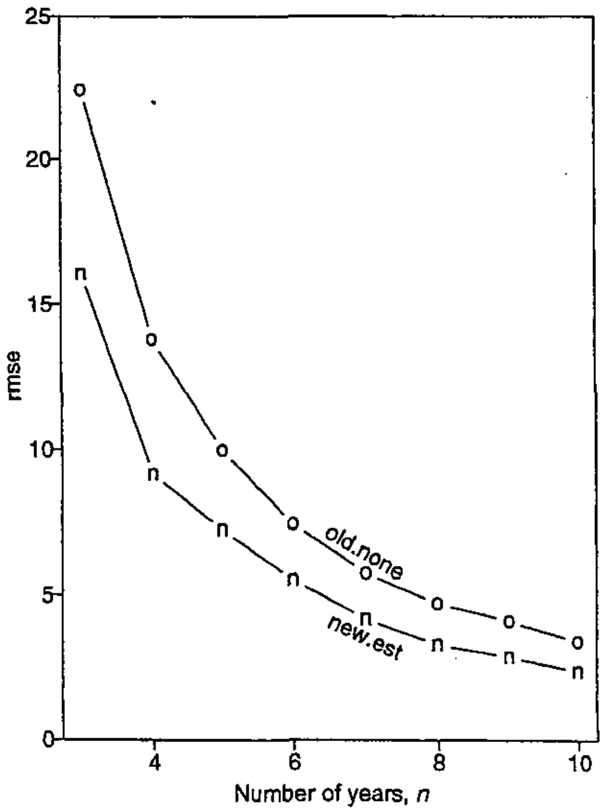

Figure 5: rmse estimates from the third set of scenarios, showing the effect of the parameter n for methods old.none and new.est.

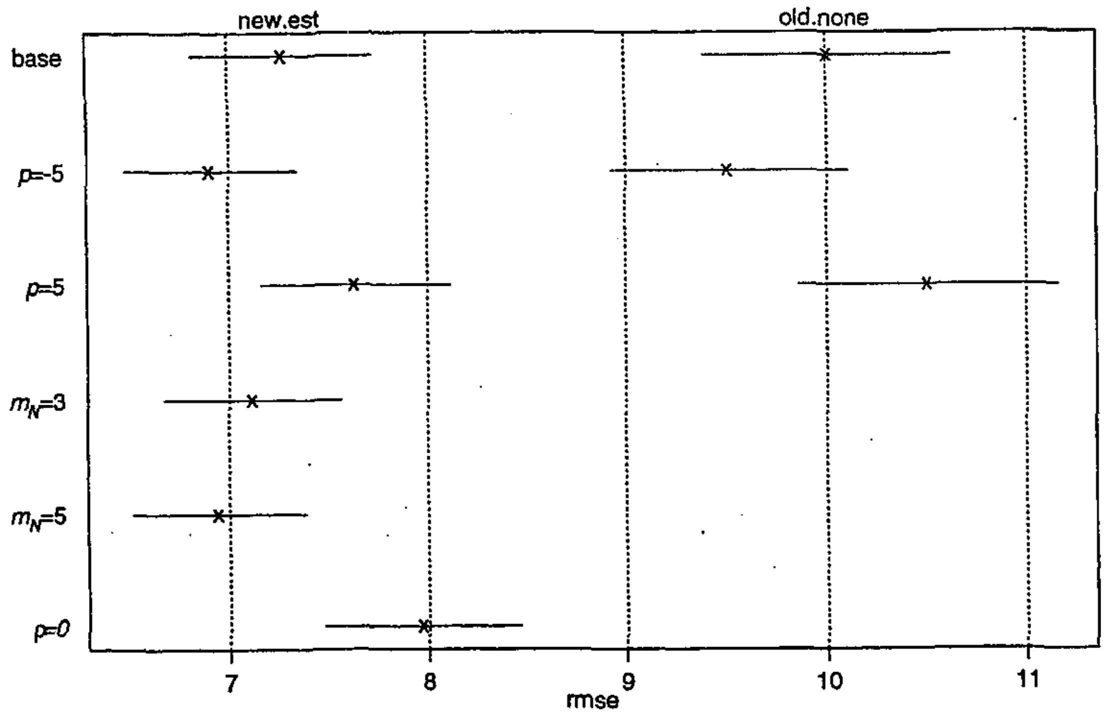

Figure 6: rmse estimates ('x', with 95% confidence interval plotted as a horizontal line) for methods old.none (grey) and new.est (black) from the first set of scenarios, showing the effect of selected parameters. No results are shown for method old.none for the lower three scenarios because neither changing m_N nor setting the correlations to zero affects this method.

The inferences that are drawn from this study are, of course, only as good as the assumptions underlying our simulations. A key assumption is that the information in Section 4 provides an adequate basis for simulating future surveys, of both the old and new designs. Another important assumption is that the loss of acoustic information in a survey of the new design is equivalent to that from reducing the number of snapshots in the north from five to two (if we do a survey of the new design in 2004 we will then be in a better position to evaluate this assumption). We have tried to protect against errors in these assumptions by considering alternative values for all parameters. It is reassuring that the new.est method showed greater precision (lower rmse) than the old.none method in all scenarios.

In our simulations, there were surveys in every year and it is straightforward to show that the same conclusions would hold if the surveys were less frequent but still regular (Francis 2003). We can see no reason to doubt that our main conclusion (that the new.est method is superior to old.none) would hold if surveys were at irregular intervals.

It is a bigger step to generalise from our very simple stock assessment model to the much more complex model used in hoki assessments. The WCSI hoki survey is only one of many data inputs to this assessment and its influence can depend strongly on model structural assumptions. Also, there are many output quantities (e.g., virgin and current biomass, yields, projection trajectories, risk) in the hoki assessment, rather than the single one (biomass growth rate, p) we considered in our simple assessment model. Thus, a thorough study of the influence of a change in design for the WCSI survey on the hoki assessment would be much more complicated and time-consuming. The additional effort of such an extended study does not seem worthwhile. It would be likely to show that the advantages of new.est over old.none are greater in some situations and less (probably non-existent) in others, but it does not seem likely to us that it would find situations in which new.est was markedly worse than old.none.

Francis (2003) examined a problem similar to that addressed in this study, but reached a much less clear-cut result. The design he considered also depended on dividing the survey area into two parts, but it produced only two biomass estimates (acoustic for one part, and trawl for the other). That design performed poorly if there was any trend from year to year in the proportion of biomass in each part of the survey area. With the design proposed here there is relatively little sensitivity to such a trend.

The overall uncertainty of the 2000 acoustic survey calculated for these simulations was much lower than that currently used in assessment (0.60). This is related to differences in the treatment of uncertainty due to species mix and our assumptions about proportions of mix marks in northern and southern areas. In the calculation of c.v.s for stock assessment (O'Driscoll 2002), there was no north-south division. Total backscatter (before any species mix correction was carried out) from all areas was split into two categories: 'mix' and 'schools'. Because mix and school marks were not explicitly separated during the mark identification for early surveys, the proportion of total backscatter in the northern strata was used as a proxy for the proportion in mix marks. In 2000, about 60% of the total backscatter was in the northern area, so we assumed that 60% of backscatter was in mix marks. This is an approximation because some hoki schools occur in northern areas and there is also mix in the southern areas (O'Driscoll et al. 2004), but it is the best we can do, short of repeating the mark identification for all surveys. Different uncertainties were then applied to the mix and school proportions based on catch composition from trawls on these two mark types (O'Driscoll 2002). A much greater uncertainty was applied to the mix proportion (lognormal c.v. = 0.5) than to the schools (lognormal c.v. = 0.08).

In estimating uncertainty distributions for the simulations in this report, backscatter was separated into north and south rather than into mix and schools. In the north, there is a species mix correction, so uncertainty has two components. There is uncertainty in the estimate of the average proportion of hoki from trawls and this was estimated by bootstrapping (see Section 4). There is also uncertainty in the actual proportion of hoki in backscatter from the northern area. This was estimated from a lognormal distribution with c.v. of 0.3 (see Table 3). Although most of the backscatter in the north is from mix marks, the northern mark identification c.v. was lower than the lognormal c.v. of 0.5 applied to mix marks in the assessment. This is because in 2000 and in future surveys, when the species mix correction is carried out based on trawl data collected during the survey, there will be more certainty about the actual proportion of hoki in the mixed marks than in surveys before 2000 when there was no trawling. The distribution of uncertainty associated with mark identification for the southern area had the same lognormal c.v. (0.08) as school marks. This southern uncertainty distribution was based on catch composition from trawls in the southern area, but southern trawls were mostly on hoki school marks and the estimate of uncertainty reflected this. If there is a significant proportion of hoki in mix marks in the southern area, as suggested by the re-analysis of the 2000 survey (O'Driscoll et al. 2004), then these simulations may underestimate the uncertainty in the southern acoustic estimate.

The uncertainty distributions in the simulations probably do not affect the general conclusion that new.est is better than old.none, although the magnitude of the gain in information may change. However, the sensitivity of survey c.v.s to the treatment of uncertainty in mark identification is a concern and needs to be investigated further.

8. PROPOSED DESIGN FOR 2004 SURVEY

We conclude in Section 7 above that there would be a gain in information by switching from the current survey method to a new method, which produces three biomass estimates: separate acoustic estimates for the north and south, and a trawl estimate for the north based on stratified random trawling. In this section we propose a design for a 2004 survey based on this premise. To do this, we need to determine the number of acoustic transects and trawls required to achieve target c.v.s for all three biomass estimates, based on current assumptions about uncertainty.

We consider five aspects of survey design:

1. Spatial coverage
2. Number and timing of acoustic transects
3. Number of random trawls
4. Number of targeted trawls
5. Other associated work

The first four components are integral to the production of the relative abundance estimates used in stock assessment. The section on "other work" identifies research that could be carried out in conjunction with the 2004 survey.

8.1 Spatial coverage

The general area surveyed on the WCSI has remained the same throughout the acoustic time series. From 1990 to 2002, between 83 and 95% of the hoki catch from the WCSI reported on trawl-catch-effort-processing-return (TCEPR) forms was taken from within the acoustic survey area (O'Driscoll 2002). We conclude that the current survey boundaries encompass most of the main hoki spawning area on the WCSI and that no changes to the survey area are required.

The proposed design uses the same six strata as the previous surveys, but stratum areas were revised slightly using recorded depths to define stratum boundaries (Table 8). The sub-stratification of Strata 1&2 and 4 introduced in 2000 was retained to improve trawl estimates from northern strata (Figure 7).

Table 8: Proposed stratum boundaries, areas, and transect allocation for the 2004 WCSI hoki acoustic survey. Stratum locations are shown in Figure 7.

Stratum	Boundary (m)	Area (km^2)	Number of transects
1&2A	300–430	845	3–5
1&2B	430–500	759	3–5
1&2C	500–650	2 182	3–5
4A	300–430	786	7–9
4B	430–500	592	7–9
4C	500–650	1 455	7–9
5A	300–300	254	6–8
5B	position to position	529	3
6	250–750	1 878	8–10
7	position to position	565	4

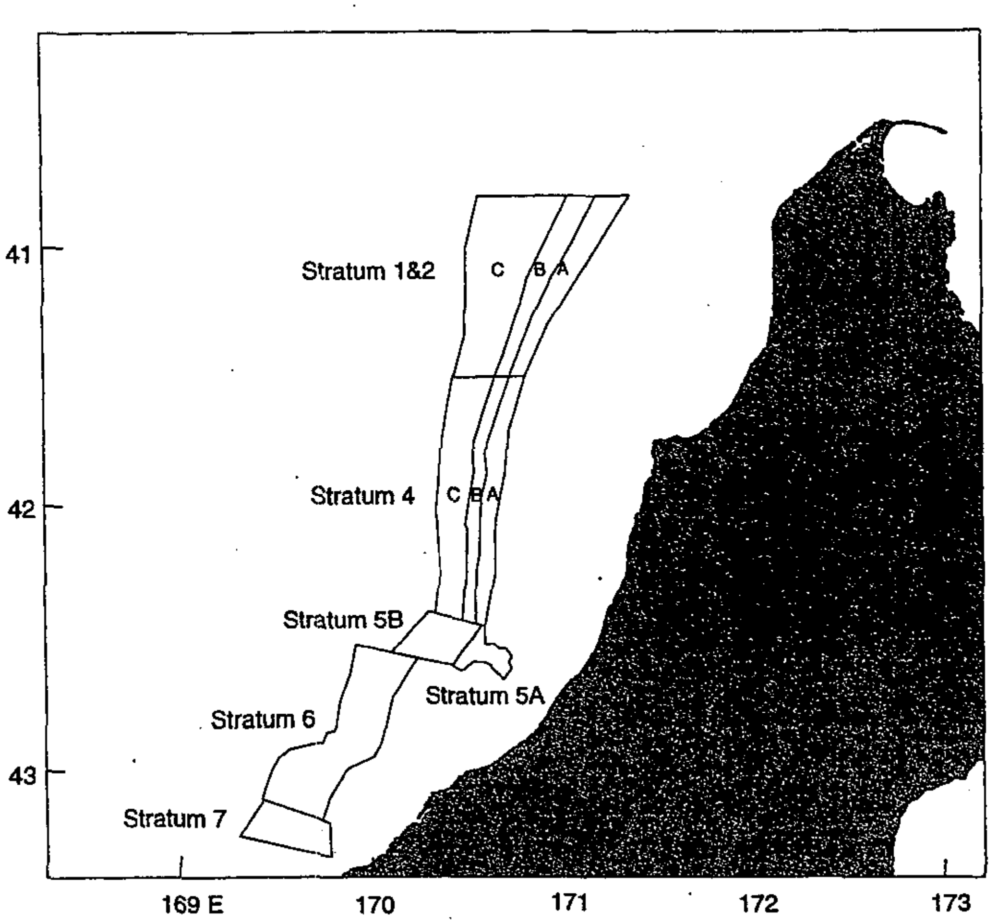

Figure 7: Proposed stratum boundaries for the 2004 acoustic survey of WCSI spawning hoki. Stratum areas are given in Table 8.

8.2 Number and timing of acoustic transects

The proposed acoustic survey design for 2004 is based on the approach used in previous WCSI surveys, and described in detail by Coombs & Cordue (1995), Cordue (2002), and O'Driscoll (2002). Briefly, this design follows the methods of Jolly & Hampton (1990), as adapted by Coombs & Cordue (1995) to produce an abundance index for transient fish populations. Estimates of the spawning biomass during the "main" spawning season were obtained from several sub-surveys or "snapshots", each consisting of random parallel transects within strata defined by depth and/or position. These estimates were then averaged to obtain an estimate of the "mean plateau height" (the average abundance during the main spawning season). Under various model assumptions, annual estimates of mean plateau height form a valid relative abundance time series (Cordue et al. 1992).

The major difference in 2004 is that two acoustic abundance indices would be produced – northern (Strata 1&2 and 4), and southern (Strata 5A, 5B, 6, and 7) – instead of the single acoustic index from previous WCSI surveys. This means that there could be different number and timing of snapshots in the two areas.

Simulations were carried out to investigate the effects of survey timing and number of snapshots on the c.v.s of the northern and southern acoustic indices. These simulations were related to those described in Section 4 and used the same parameter values, given in Table 3. However, instead of using only the snapshot dates in Table 4, simulated surveys were run with between 2 and 6 snapshots in each area, and with a range of timings from early June to late August. In these simulations, we used a constant sampling error (snapshot c.v.) of 0.16 for all northern snapshots and 0.10 for all southern snapshots

Timing was the most important consideration in survey design. Simulations indicated acoustic surveys of WCSI should have a mid-date of about 5 August (Figure 8). The c.v.s increased if surveys were either later or earlier. This pattern was consistent for both northern and southern areas because the same distributions of arrival dates and residence times were used to construct the underlying population model in both areas (see Table 3). The optimal timing of 5 August was strongly determined by these distributions. For example if the range of mean arrival dates were widened to Julian days 197–222 (16 July to 10 August) to allow mean arrival to be later in August, then the optimal survey mid-date would shift later to 12 August.

Increasing the number of snapshots also reduced the c.v., particularly in the northern area (Figure 9). In the south, the gains (in terms of reduction in uncertainty) from increasing the number of snapshots were small relative to those which could be obtained by improving survey timing (Figure 9). We might conclude, from Figure 9, that two snapshots of the southern area are sufficient to give a low c.v. (0.27) and there would be little gain from additional snapshots. This is true under the simulation conditions, which assumed that the timing of all simulated surveys, regardless of the number of snapshots, was optimal. If the timing is sub-optimal (or if our assumptions about the distributions of arrival dates and residence time are wrong), then longer surveys with more snapshots are more robust than shorter ones. For example, a survey of the southern area with five snapshots gave an estimated c.v. less than 0.3 with survey mid-dates between 28 July and 15 August, while a survey with two snapshots only gave a c.v. less than 0.3 if it was centred between 2 and 10 August (Figure 10). This was because a short survey increased the probability of missing the period of peak abundance if there was variation in the timing of the spawning season.

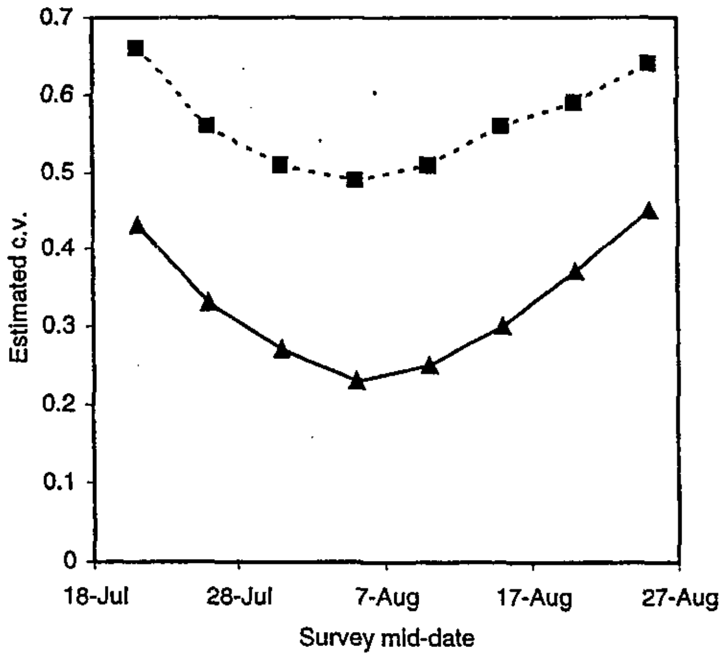

Figure 8: Effect of survey timing on simulated estimates of precision (c.v.) for northern (dotted line) and southern (solid line) areas. Simulated surveys consisted of five snapshots evenly spaced over 26 days in each area.

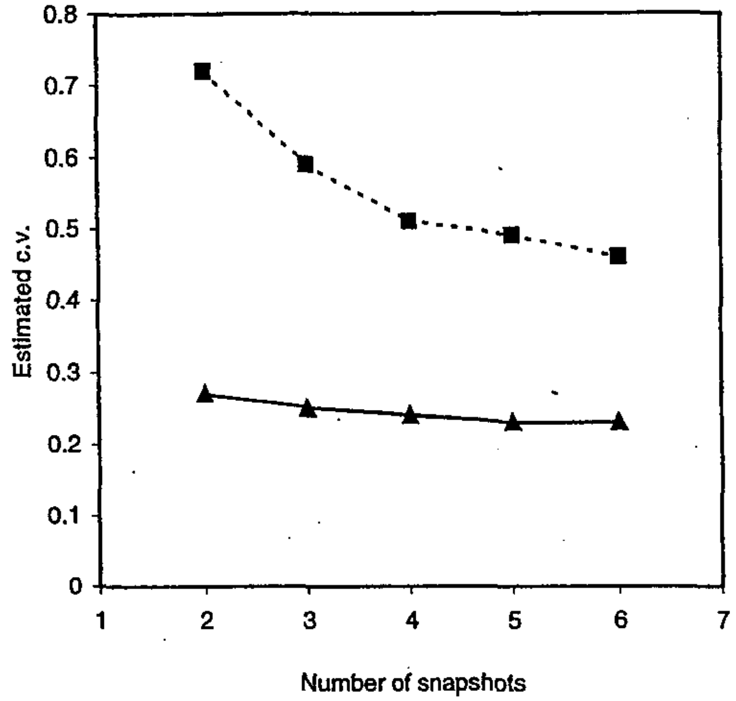

Figure 9: Effect of number of snapshots on simulated estimates of precision (c.v.) for northern (dotted line) and southern (solid line) areas. Simulated surveys in both areas were centred on the estimated optimal mid-date.

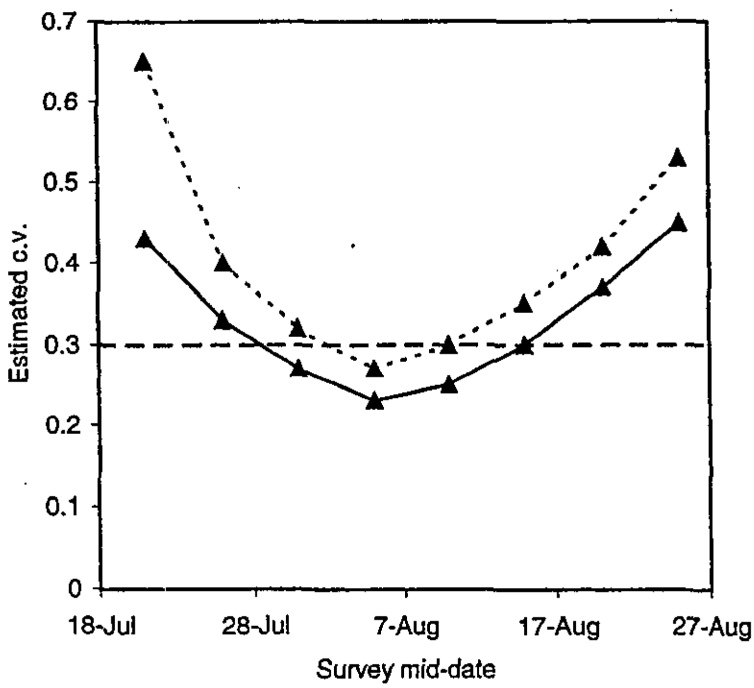

Figure 10: Effect of survey timing on simulated estimates of precision (c.v.) for southern areas with two (dotted line) and five (solid line) snapshots. The dashed line shows an arbitrary reference c.v. of 30%.

In both areas, simulations suggested there was little advantage in having a survey with more than four snapshots.

8.3 Number of random trawls

The northern trawl estimate should be obtained using a stratified random trawl survey. To allow comparison with the trawl results from the previous survey in 2000 (see O'Driscoll et al. 2004), the same vessel (*Tangaroa*) and the same eight-seam hoki trawl (see Chatterton & Hanchet 1994) should be used for all random trawls in 2004. Trawl procedures, the recording of tow parameters and species caught will follow the standardised guidelines recommended by Hurst et al. (1992). Unlike 2000, there should be no random trawling at night. All random bottom trawls should be carried out during daylight hours when a greater proportion of fish are near the bottom and catch rates are typically higher (O'Driscoll et al. 2004).

Random bottom trawls should be carried out only in the northern area. This area has been stratified by depth into six trawl strata: 1&2A, 1&2B, 1&2C, 4A, 4B, and 4C (see Table 8 and Figure 7). The proposed allocation of trawl stations was based on a statistical analysis of catch rate data from daytime random bottom trawls in 2000 using the optimisation procedure of Bull et al. (2000). A minimum of three stations per stratum was used. Target c.v.s of 0.2 for hoki, hake, and ling, and 0.25 for silver warehou were used in the statistical analysis. The proposed station allocation for 2004 is given in Table 9.

The proposed sampling design (Table 9) gives a similar number of stations as the survey in 2000, when there were 47 random daytime bottom trawls in the northern area. In 2000, c.v.s of 0.22 for hoki, 0.17 for ling, 0.14 for hake, and 0.25 for silver warehou were achieved (O'Driscoll et al. 2004).

Table 9: Proposed trawl station allocation for daytime random bottom trawls in the northern area during the 2004 WCSI hoki acoustic survey. Numbers are the number of stations required to achieve a target c.v. of 0.2 for hoki, ling, and hake, and 0.25 for silver warehou. Stratum locations are shown in Figure 7.

	Number of stations				
Stratum	Hoki	Ling	Hake	Silver warehou	All
1&2A	5	7	3	8	**8**
1&2B	6	3	3	9	**9**
1&2C	8	4	4	3	**8**
4A	12	5	3	10	**12**
4B	6	3	3	3	**6**
4C	8	3	6	3	**8**
Total	45	25	22	36	**51**

Random bottom trawls will also be used to provide estimates of the proportion of hoki in the bottom referenced mixed layer to decompose the acoustic estimates in the northern area.

8.4 Number of targeted trawls

In any acoustic survey, it is necessary to identify the acoustic marks and determine which contain the target species. Some mark identification in hoki surveys is possible based on our prior knowledge about mark characteristics, depth, and behaviour. However, directed trawling is also required to identify new, different, and ambiguous (that is targets which are not easily classified) marks. "Typical marks" also need to be fished on occasionally for confirmation, as fish behaviour and mark type can change over time.

Targeted trawls are also required to improve our understanding of species composition. In the northern area, the acoustic species decomposition in 2004 should be based mainly on random bottom trawl catches. This assumes that the bottom trawl representatively catches all species in the mixed layer. This assumption introduces considerable uncertainty, which is currently incorporated when estimating the survey c.v. (O'Driscoll 2002). Further research is required, including fishing with other gear types (e.g., finer mesh trawls) and midwater trawling on species mix layers away from the bottom to further investigate species composition in northern mixed species marks.

The current assumption is that most of the hoki biomass in the southern strata comes from hoki schools. This was not the case in 2000. Low density hoki mix marks, similar to those observed in the northern strata were common in Strata 5B, 6, and 7 (O'Driscoll et al. 2004). O'Driscoll et al. (2004) recommended that future surveys should include increased trawling in these southern strata to assess the extent of the species mix problem.

The number of targeted trawls required will depend on the marks observed during the survey. Based on the re-analysis of the 2000 WCSI survey (O'Driscoll et al. 2004), and our experience in recent surveys of Cook Strait (e.g., O'Driscoll 2003), we suggest a minimum of six targeted trawls per snapshot in the southern area and three targeted trawls per snapshot in the northern area. More targeted trawling is required in the south because there tends to be a wider range of mark types in this region and there is no random trawling component. We anticipate that additional information on mark identification and composition will also be available from the commercial fishery, especially in the area around the Hokitika Canyon (Strata 5A and 5B).

Targeted trawls should be carried out with a variety of gear types, including midwater, bottom, and fine-mesh trawls, depending on the location of the acoustic ark. There is no specific vessel requirement for targeted trawling.

8.5 Other work

A 2004 WCSI hoki survey could also include work that is not directly related to the production of a hoki abundance estimate.

Acoustic target strength (TS) is still an important area of research. There are currently several contradictory length-to-target strength relationships for hoki obtained from in situ measurements and swimbladder modelling (Macaulay et al. 2002). To attempt to resolve these differences and improve our estimates of hoki TS, further in situ data could be collected during the 2004 survey. It is also necessary to collect further data on TS of associated species, as these are important inputs into the species decomposition and calculation of proportion of hoki backscatter in the northern strata. Collection of in situ acoustic TS data would require additional time outside the acoustic survey framework. However, suitable marks could be located during the acoustic survey, minimising the need for searching.

Macaulay & Dunn (2000) investigated the feasibility of using acoustics to estimate hake biomass on the WCSI, and suggested an acoustic survey for hake could be combined with a hoki acoustic survey. The WCSI (HAK 7) is the largest hake fishery in New Zealand, with a catch of 8383 t in the 2000–01 fishing year (Annala et al. 2003). There are no fisheries independent biomass indices available for HAK 7 and the status of this stock is uncertain (Annala et al. 2003). Because hake and hoki are found in similar areas on the WCSI during winter, acoustic data on hoki and hake could be collected concurrently, with only a small increase in survey time (Macaulay & Dunn 2000).

8.6 Survey duration

About 78 hours would be required to complete an acoustic snapshot of either the northern or the southern area. This was based on an average of 400 n. mile of transects and travel between transects and three targeted trawls per snapshot in the north and 360 n. mile of transects and travel and six targeted trawls per snapshot in the south. Distances were calculated from cruise tracks from Snapshot 3 of the survey in 2000, which had an average number of transects (see Table 8), and converted to times using an average speed of 6 knots. The actual transect speed is usually 8 knots, but allowance was made for turns, bad weather, and routine maintenance of acoustic equipment. Targeted trawls take an average of 3 h each.

Based on our experience in 2000, an average of four random bottom tows could be carried out during daylight hours each day (N. Bagley, NIWA, pers. comm.). This means that 13 days would be required to complete the 51 random trawls required for the trawl estimate of the northern area. Acoustic transects could also be run in the northern strata during the night, and two acoustic snapshots (with targeted trawls) could be completed in 13 nights. Thus, the minimum time required for the northern part of the survey would be 13 days on the ground, to carry out random trawls and two acoustic snapshots. If further acoustic snapshots of the northern area are required, these could be run during the day and night, taking about 3 days (78 h) for each additional northern snapshot. In the southern area, acoustic transects would be run day and night, with each southern snapshot taking 78 h.

Table 10 shows the estimated time on the grounds required (to the nearest day) for surveys of the northern and southern areas with various numbers of acoustic snapshots. The simulated c.v.s are also given based on an optimal timing (survey centred on 5 August). For a single vessel, the total survey time is the sum of the times for the northern and southern components. We recommend that the minimum requirement for a combined survey in 2004 is two acoustic snapshots in the northern area, a northern trawl estimate, and three acoustic snapshots in the southern area. This would require approximately 13 + 10 = 23 vessel days in the survey area.

Table 10: Estimated days on the ground* for surveys of the northern and southern areas of the WCSI with 51 random trawls in the north and varyious numbers of acoustic snapshots. This time budget allows 3 targeted trawls during each northern acoustic snapshot and 6 targeted trawls during each southern snapshot. The simulated c.v.s are based on optimal survey timing under the best available assumptions about hoki arrival *date and residence time (see Section 8.2).*

	Northern area		Southern area	
Number of snapshots	Survey days	Minimum c.v.	Survey days	Minimum c.v.
2	13	0.72	7	0.27
3	16	0.59	10	0.25
4	20	0.51	13	0.24
5	23	0.49	16	0.23
6	26	0.46	20	0.23

* Approximately 3 days are also needed for vessel mobilisation and demobilisation, and steaming to and from Wellington.

To ensure comparibility with the 2000 survey, all random trawls would need to be carried out from *Tangaroa.* There is no specific vessel requirement for the rest of the acoustic survey. The survey vessel would need to carry calibrated acoustic equipment, preferably a towbody system, and be able to carry out directed fishing on marks using both midwater and bottom trawl gear. It would be possible to carry out the proposed survey using two or more vessels. For example, the northern trawling and acoustic snapshots could be carried out by *Tangaroa,* while the southern snapshots could be carried out from another vessel.

Options for survey vessels other than *Tangaroa* include *Kaharoa* and commercial vessels. Because *Kaharoa* is a much smaller than *Tangaroa,* it would be unable to work in rough sea conditions and the average time taken to complete a snapshot would likely increase. However, *Kaharoa* is used successfully to survey spawning hoki in Cook Strait and could potentially be used in the southern strata, which are relatively close to the coast.

The potential for using industry vessels to survey hoki on the WCSI is being investigated during the 2003 hoki season in a collaborative project between NIWA and the Hoki Fishery Management Company. An industry vessel may be more cost effective if the vessel can "pay for itself" by continuing to fish commercially during the survey. However, because of the size of the WCSI survey area, the fishing success of the vessel is likely to be reduced when transects are away from the peak hoki densities, and this will reduce the savings. Snapshots from an industry vessel would also take longer if the vessel is commercially fishing. A major limitation for an industry vessel using its own hull-mounted acoustic system (e.g., ES-60) is the weather. Signal quality from hull-mounted transducers deteriorates markedly at wind speeds greater than about 20 knots and swell heights greater than about 2 metres. Such conditions occur frequently during the hoki spawning season. During surveys on research vessels lost days are minimised by using a towbody which gets the acoustic transducers down about 30 metres below the surface. Currently, the NIWA towbody system is not easily deployed from an industry vessel, but consideration is being given to designs for a portable system which could be easily used from an industry vessel.

9. ACKNOWLEDGMENTS

Alistair Dunn reviewed an earlier draft of this document. The work was funded by the Ministry of Fisheries (Project HOK2002/03).

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Appendix 1 Equations for maximum-likelihood estimation

In this Appendix we describe the likelihood equations used for all five methods of Table 1 and derive estimation equations for two of these methods.

If surveys are carried out in years y_j, for $j = 1,...,n$, the negative log-likelihood, λ, for the observations for a survey using method new.est is given by

$$\lambda = \sum_j \left(\log \mathbf{O}_j - \boldsymbol{\mu}_j\right)^{\mathrm{T}} \mathbf{V}_j^{-1} \left(\log \mathbf{O}_j - \boldsymbol{\mu}_j\right)$$

where $\mathbf{O}_j$ is the vector of observations (O_{ANj}, O_{ASj}, O_{TNj}), $\boldsymbol{\mu}_j$ and $\mathbf{V}_j$ are the expected value and variance of $\log\mathbf{O}_j$, $^{\mathrm{T}}$ indicates the matrix transpose operation, and constants are ignored. $\boldsymbol{\mu}_j$ and $\mathbf{V}_j$ are given by

$$\boldsymbol{\mu}_j = \left(\log\left(q_A \pi_{Nj} B_{y_j}\right) - 0.5\sigma_{ANj}^2, \log\left(q_A\left(1-\pi_{Nj}\right)B_{y_j}\right) - 0.5\sigma_{ASj}^2, \log\left(q_T \pi_{Nj} B_{y_j}\right) - 0.5\sigma_{TNj}^2\right)$$

$$\mathbf{V}_j = \begin{pmatrix} \sigma_{ANj}^2 & \rho_A \sigma_{ANj} \sigma_{ASj} & \rho_T \sigma_{ANj} \sigma_{TNj} \\ \rho_A \sigma_{ANj} \sigma_{ASj} & \sigma_{ASj}^2 & 0 \\ \rho_T \sigma_{ANj} \sigma_{TNj} & 0 & \sigma_{TNj}^2 \end{pmatrix}$$

and $\sigma_{ANj}^2 = \log\left(1 + c_{ANj}^2\right)$ etc.

The likelihoods for the other four methods can be simply derived from that for new.est. For new.fix, we need only replace π_{Nj} by π_N. For the old.fix and old.est methods the likelihood is the same for new.fix and new.est except that we remove the third element in the vectors $\mathbf{O}_j$ and $\boldsymbol{\mu}_j$, and the third row and column from $\mathbf{V}_j$. For old.none the equation simplifies substantially to

$$\lambda = 0.5 \sum_j \left[\sigma_{Aj}^{-1} \log\left(\frac{O_{Aj}}{q_A B_{y_j}}\right) + 0.5\sigma_{Aj}\right]^2$$

We assume, for all methods except old.none, that our observation-error c.v.s do not vary from year to year, so for these methods we can write σ_{AN} in place of σ_{ANj}, σ_{AS} in place of σ_{ASj}, etc.

We are using maximum-likelihood estimation, so our aim is to find parameter values which minimise λ. For methods old.est, new.est, and new.fix we found no analytical solution to the minimisation problem, so we used a numeric minimisation algorithm (function ms in Splus, see Chambers & Hastie 1992) to find the maximum-likelihood estimates. However, there is an analytic solution for the other two methods. We now derive this solution for old.fix, but give only the estimator for p because the other parameters are not of interest in this study.

For method old.fix we can rewrite the likelihood as

$$\lambda = \frac{1}{2\sigma_{AN}^2(1-\rho_A^2)}\sum_j\left[\log(O_{ANj}) - \log\pi_N - \alpha_A - y_j\gamma + 0.5\sigma_{AN}^2\right]^2$$
$$+\frac{1}{2\sigma_{AS}^2(1-\rho_A^2)}\sum_j\left[\log(O_{ASj}) - \log(1-\pi_N) - \alpha_A - y_j\gamma + 0.5\sigma_{AS}^2\right]^2$$
$$-\frac{\rho_A}{\sigma_{AN}\sigma_{AS}(1-\rho_A^2)}\sum_j\left\{\left[\log(O_{ANj}) - \log\pi_N - \alpha_A - y_j\gamma + 0.5\sigma_{AN}^2\right]\right.$$
$$\left.\left[\log(O_{ASj}) - \log(1-\pi_N) - \alpha_A - y_j\gamma + 0.5\sigma_{AS}^2\right]\right\}$$

where $\alpha_A = \log(q_A B_{\text{init}})$ and $\gamma = \log(1 + p/100)$. At the maximum-likelihood estimate all partial derivatives are zero, so

$$\frac{\partial\lambda}{\partial\alpha_A} = 0 = \theta_N\sum_j\left[\log(O_{ANj}) - \log\hat{\pi}_N - \hat{\alpha}_A - y_j\hat{\gamma} + 0.5\sigma_{AN}^2\right]$$
$$+\theta_S\sum_j\left[\log(O_{ASj}) - \log(1-\hat{\pi}_N) - \hat{\alpha}_A - y_j\hat{\gamma} + 0.5\sigma_{AS}^2\right]$$

$$\frac{\partial\lambda}{\partial\gamma} = 0 = \theta_N\sum_j y_j\left[\log(O_{ANj}) - \log\hat{\pi}_N - \hat{\alpha}_A - y_j\hat{\gamma} + 0.5\sigma_{AN}^2\right]$$
$$+\theta_S\sum_j y_j\left[\log(O_{ASj}) - \log(1-\hat{\pi}_N) - \hat{\alpha}_A - y_j\hat{\gamma} + 0.5\sigma_{AS}^2\right]$$

where $\theta_N = \dfrac{\sigma_{AS} - \rho_A\sigma_{AN}}{\sigma_{AN}^2\sigma_{AS}(1-\rho_A^2)}$, $\theta_S = \dfrac{\sigma_{AN} - \rho_A\sigma_{AS}}{\sigma_{AS}^2\sigma_{AN}(1-\rho_A^2)}$, and ^ denotes a maximum-likelihood estimator (the equation $\partial\lambda/\partial\pi_N = 0$ is omitted because it is not needed for the estimation of p).

It is straightforward to solve these equations to obtain

$$\hat{\gamma} = \frac{U_{AN} + U_{AS}}{(s_2 - s_1^2/n)(\theta_N + \theta_S)}$$

where $s_k = \sum_j y_j^k$, $U_{AN} = \theta_N\left[\sum_j y_j \log(O_{ANj}) - (s_1/n)\sum_j \log(O_{ANj})\right]$, and U_{AS} is defined analogously. Thus our estimator for p is

$$\hat{p} = 100\left[\exp\left(\frac{U_{AN} + U_{AS}}{(s_2 - s_1^2/n)(\theta_N + \theta_S)}\right) - 1\right]$$

In this report we consider only the special case where surveys occur every year, which means $y_j = j$, so $s_2 - s_1^2/n = n(n^2-1)/12$.

For method old.none the derivation is similar but becomes slightly messier, because we allow c_{Aj} to vary from year to year. However, estimator can be written in a pleasingly similar form:

$$\hat{p} = 100\left[\exp\left(\frac{U'_A}{\left(s'_2 - s_1'^2/\theta'_A\right)\theta'_A}\right) - 1\right]$$

where $\sigma_{Aj}^2 = \log\left(1 + c_{Aj}^2\right)$, $s'_k = \sum_j y_j^k / \sigma_{Aj}^2$, $\theta'_A = \sum_j \sigma_{Aj}^{-2}$, and $U'_A = \theta'_A\left[\sum_j y_j\left(\left(\log O_{Aj}/\sigma_{Aj}^2\right) + 0.5\right) - \left(s'_1/\theta'_A\right)\sum_j\left(\left(\log O_{Aj}/\sigma_{Aj}^2\right) + 0.5\right)\right]$.